Geology. — *On a new Basis of Solution of the Caldera-Problem and some associated Phenomena.* By C. G. S. SANDBERG D.Sc. (Second communication.) (Communicated by Prof. Dr. G. A. F. MOLENGRAAFF.)

(Communicated at the meeting of February 25, 1928).

In our previous communication (17) our consideration of the caldera-problem was based, more especially, on the mode of occurrence of the phenomena in strato-volcanoes, and on that of the migration of eruption points. Accordingly we tested our conclusions on well established facts in the history of Vesuvius, that volcano being the most carefully observed and described specimen of its type.

We now shall use the results of the studies of the classical type of lava-volcanoes *(Schildvulkane)*, the Hawaiïan and specially Kilauea, as testing material for our contention regarding the real nature of the caldera phenomenon, this lava-volcano, like Vesuvius, having been very closely observed during several decades.

Halemaumau, its still active eruptive centre, is situated in the south-western part of the great Kilauea-caldera, the vertical wall of which encompasses an area of some 5 by 3 km in diameter.

Inner-peripherically situated remnants of former eruption-channels of similar order may be located, S. of Volcano-House, at the N. E. corner of the caldera and in its south eastern part, the Sulphur Bank. Also, in 1888 (see WILKES and BRIGHAM's map [13] (Pl. IX)) two smaller specimen were situated on the edge of the then "black ledge" and two others occurred a little nearer to the north western part of the caldera-wall (Fig. 1 ; i.k. and l.m. respectively). These four eruption-points and the

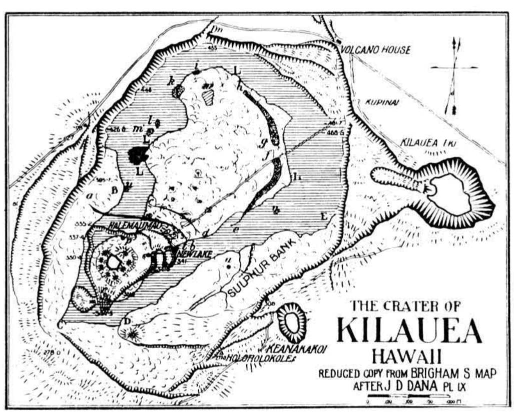

Fig. 1.

lava-dome, to the S. of the last two mentioned, trend in a direction parallel to the north western part of the Kilauea-wall. Such concentric arrangement of eruption-points is repeated in the "black ledge" round Halemaumau (p.q.r.s.), where they occur *outer*-peripherically in relation to the present eruptive channel of Halemaumau and at the same time *inner*-peripherically in relation to a former, wider eruptive channel, the remnants of which surround the present one and the intervening black ledge.

Outer-peripherically arranged round the Kilauea caldera-wall we find Kilauea-Iki, a "depression" to the W. of it and Keanakakoi, and this phenomenon is repeated round Halemaumau by the mode of arrangement of the so-called "New Lake", a "depression" to the N. W. of it, and a similar one on the extreme S. W. of the old cone-pipe-wall of Halemaumau above referred to.

As further examples of main orifices surrounded by peripherically arranged secondary eruption-points we may mention Mauna Loa, Kea (19), the volcanoes of the Samoa Islands etc. etc. (20).

DANA's contention that the vertical wall encompassing the Kilauea caldera is nothing but a remnant of the cone-pipe-wall of the then Kilauea volcano is now accepted by JAGGAR, PENCK, ARN. HEIM, PERRET, among others, in so far that they agree that "Halemaumau is a volcano in a volcano", as ARN. HEIM expresses it (21). Curiously enough, however, the latter still qualifies this Kilauea-wall as that of an "Abbruchskrater", a "cratère d'effondrement", the down-throw of which would have resulted from undermining through fusion of its support (l.c. text to Pl. I). This contention seems in flagrant contradiction with established facts of Kilauean history and appears to be based, among other things, on an erroneous way of extrapolating observed phenomena of secondary moment.

In order, to make the gist of my argument clearer, I reproduce DANA's combined section of Kilauea, showing the successive changes in the form of its crater (cone-pipe) during the period 1823—1886 [13] (p. 127) (compare also his maps, sketches and descriptions). This section clearly shows e.g. how, in the course of time, the crater of Kilauea narrowed down to that of Halemaumau.

A study of DANA's section and descriptions clearly shows that ever since

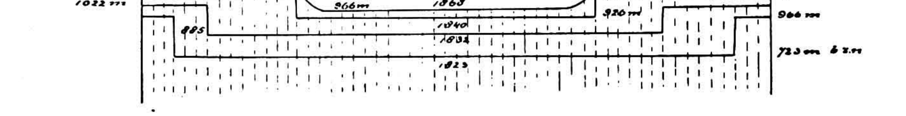

Fig. 2. Schematical combined section of the Kilauea-Caldera showing its mode of development subsequent to its principal eruptions during the period 1823—1886. After J. D. DANA. The broken vertical lines, added to the original by me, represent the directions of the dividing planes between successive accretions. Those between successive depositions, by overflows, have not been indicated to avoid crowding.

the 1823 eruption (and probably even before that of 1790) the absolute height above sea-level of the top of the caldera-wall of Kilauea, as well as its shape remained unchanged ; i.e. during that period there occurred no elevation, subsidence (downthrow), or caving in of the caldera wall of sufficient importance to support the contention that the occurrence of this wall is of secondary origin, as is implied by current theories. In 1823 a narrow terrace extended (300 m below the western top-rim of the wall) all along the inner side of the caldera-wall of Kilauea. It was the black ledge of that time, the vertical inner wall of which enclosed the then crater-floor, the bottom of the "lower pit".

Now, how was this, and how were the younger terraces successively formed ?

By down-throws or subsidences ? By outblasts ? or in some other way ?

It is clear that a positive answer to these questions, if it could be given, might be decisive as to the origin of calderas.

We cannot affirm, on the evidence of direct observation at least, that the terrace of 1823 was actually formed in some other way, however much we may be justified in doing so on the basis of anology.

In fact, if this and subsequent terraces were formed by downthrow, collapse or out-blast, then any such process of presumed caldera-formation would necessarily have caused :

1. an outward displacement of the caldera-wall or (and) of that of the enclosed cone-pipe-wall ; i.e. a permanent *enlargement* of either or both ;

2. part of the former mass surrounding the eruption-channel, i.e. part of the (presumed) original cone and (or) its floor, to occupy a lower level after the supposed event than it did before (compare fig. 1 (17)).

Now, when considering how the Kilauea-caldera and its enclosed eruption-channel, the lower pit, fared after 1823, we find that no outward displacement of the Kilauea-wall worth mentioning has taken place, nor, we repeat, any material change of its altitude above sea-level, in spite of various eruptions since 1823. It is therefore most probable that the then terrace below the wall-rim was no more a product of subsidence, downthrow or outblast than are those of later formation. In fact, not only did no enlargements of the caldera space or of the magmatic conduit occur, subsequent to the eruptions between 1823 and 1886, *but the contrary actually happened, in so far that the capacity of the latter, that of the "lower pit", narrowed during each eruption until it was finally restricted to the dimensions of Halemaumau, the present eruptive channel.*

Correspondingly the surface of the black ledge, enclosing the channel, broadened and also assumed a **higher** *level than that of its predecessor, because of the deposition of fresh ejectamenta on its former surface.*

Thus, the surface of the caldera-floor acquired its maximum height and development subsequent to the eruption of 1886. It then extended as a slightly convex plane, over the entire space enclosed by the encompassing wall of Kilauea, at an altitude which was only 132 m below that of its western rim, a formation exactly like those of Askja, which is enclosed by Dyngjufjöll, and of Ngorongoro (East Africa). Consequently, if volcanic activity at Kilauea had ended then or had remained latent until the present

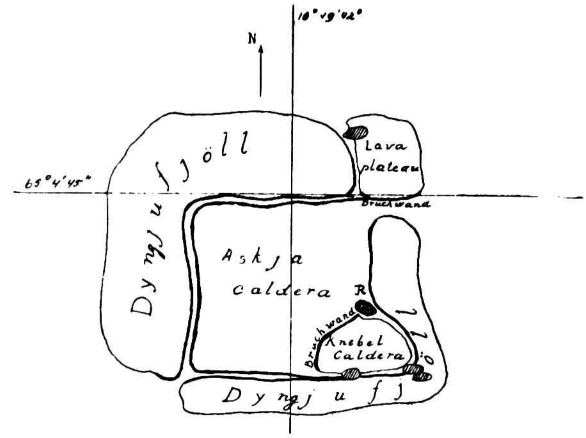

Fig. 3. Sketch of the Dyngjufjöll-Askja-Knebel-Complex. After H. RECK's topographical map [6], illustrating how the phenomenon of migration of younger eruption centres is repeated again and again.

Askja-caldera < Lava plateau / Knebel-caldera < Rudolf crater (R) / S. E. craters (shaded) / S. fumaroles „

day, whilst its previous history were unknown, (as is that of Ngorongoro, Askja-Knebel, and similar occurrences) then we should now search in vain, within the encompassing wall of the Kilauea-caldera, for the "central eruption channel" from which such a lava-floor emanated at one time.

From the foregoing it is clear that, in the course of time, the caldera of Kilauea went through a process of filling up identical with that of Vesuvius (17) (p. 1175—76). Far from being caused by downthrow, crumbling or explosions, it is this process which originated the successive terraces, black ledges, each younger one being broader and occupying a higher level than its predecessor, within the encompassure of the stable caldera wall. Why they will, inherently, be bordered, outwards *and* inwards, by *grosso modo* vertical walls, we have already explained (17).

Summarizing, we may conclude that the vertical wall encompassing the Kilauea-caldera is nothing but a top part of the cone pipe-wall of the old Kilauea-volcano, i.e. a product of primary origin. Further it is established that the successive terraces have been built up concomitantly with the narrowing-down process to which the magmatic conduit of Kilauea was subjected.

Still, there is no doubt that the phenomenon of subsidence and downthrow and temporary enlargement of the said conduit did take place at Kilauea at the close of various of its eruptive periods. And although of secondary importance to the problem of caldera-*formation*, it is very likely that a misappreciation of the real nature of these phenomena and a false extrapolation furnished considerable support to the subsidence theory. Hence it seems necessary to identify that real nature.

Our analysis of the mechanism of volcanic cone-building (17) showed that cone-pipes in course of erection are being built up, generally speaking, under the influence of gravity, inter-friction and pressure of the extruding magmatic column on the accumulating ejectamenta; i.e. that of a gas-current laden with fragments and particles of eruptive and other rock-material, or of a column of more or less plastic rock material highly charged with magmatic vapours and gasses. At the same time we showed that the material constituting the conepipe-wall would, *eo ipso*, arrive in a state of *labile* equilibrium the moment the intensity of the pressure of the said magmatic column changed. Hence the occurrence of subsidence phenomena, falling in *of the orifice* of the cone-pipe and its subsequent, though often temporary, enlargement which is wont to follow immediately on periods of eruption, e.g., of strato-volcanoes (Vesuvius and others, [3]).

It is clear that these phenomena of subsidence, collapse and temporary enlargements of the cone-pipes of *lava-volcanoes (Schildvulkane)*, which are also wont to follow their periods of eruption (22) (23) (24), are identical in origin and nature with those of strato-volcanoes. In fact, under the influence of the cooling and solidifying effect of the upper surface and of the sides of the cone pipe-walls, a rising lava-column will tend to "cake on" (accretion, plastic lining, etc.) and so cause a shore or black ledge, of zonal structure. It is clear, however, that the viscosity (solidification) of such a shore or black ledge, will decrease with increasing depth; i.e. the cone pipe-wall will tend to liquefaction more and more with both, depth and vicinity to the incandescent magmatic rock increasing. Now, this peripherical part of such a zonal shore or black ledge will remain in a state of equilibrium, *grosso modo*, so long as the surface of the lava-column is at or near the level of its surface. On the retreat of the lava-column, however, such parts of the newly formed black ledge [1]) as have not reached a sufficient degree of solidification will tend to subside or collapse and in doing so may drag with them, to a greater or less degree, more distant parts of the black ledge or cone-pipe.

As a matter of fact the phenomenon described above was witnessed by PERRET at Halemaumau. He wrote (22):

"But the shore [2]) — undercut and plastic in its foundations — soon yielded to gravity as the support of the lava column was withdrawn, and settled......, whereupon the unsupported black ledge began to give way in a series of majestic downfalls...... Although on a smaller scale, the collapse of these previous formations was comparable to that of Vesuvius after the eruption of 1906. At the west and north sides the rock of the wall was

[1]) The "shore" by PERRET (see note 2).

[2]) Recently accretioned black ledge (see note 1).

under a powerful stress and detachment was accompanied by a sharp report as, with a crushing roar, the avalanche of broken rock descended in a cloud of stony dust...... At the east edge, on the contrary, detachment was gradual, the dislocated masses of rock sliding downward with a long-drawn roll of thunder......" (See also (24) a.o. p. 219, Conclusions.) (Compare also the descriptions of subsidence phenomena at the Knebel-caldera subsequent to its great eruption, by WATT, JOHNSTRUP and others [6] [12].)

It is clear that these phenomena do not affect the problem of caldera-*formation* in the least and that they concern, exclusively, that of an *enlargement*, often only temporary and relatively minimal at that, of an existing magmatic conduit *by means of subsidence of part of a newly formed or even adjacent black ledge along their planes of zonal accretion.*

It would seem that our study of the caldera-problem has led us to another important result. In fact, it has shown that the filling-up process of a caldera-space, often of gigantic dimensions, is accomplished by lateral accretions from a conduit and by depositions on its surroundings of the products of its overflow, in such a manner that an eruptive massive causally ensues in which zones of less and greater resistance will alternate, irregularly yet systematically. The divisional planes between successive layers of accretion and deposition will constitute, *grosso modo,* a system of planes of least resistance.

Moreover, it is clear that a tendency to a certain mode of orientation will be inherent in these alternating zones of less and greater resistance and that such orientation will largely correspond with the physical state of the rock-material concerned, during its deposition or accretion. Should the rock have been extremely liquid (Kilauea and, in general, the basaltic group of rocks), then it may be expected that the zones will be directed in a vertical and horizontal sense corresponding respectively with the orientation of the accretions and depositions. For more viscous material, these directions may be expected to vary accordingly.

Furthermore it is equally clear from the foregoing that certain directions of trend will be imposed genetically on these zones of less and greater resistance e.g. one which is parallel, generally speaking, to the wall of the eruption channel concerned.

Now, should our conclusions be right, then it may be reasonably expected that gravitative, magmatic, and other tensions will naturally tend for relief, along the directions indicated above, in the shape of faultplanes, subsidences, zones of disruption, fissures, eruption-points, fumaroles, etc. etc. Finally it should be kept in mind that such layers of accretion and deposition, may acquire any shape, size, and thickness, ranging from a thin wafer to a big mass, and that consequently their dividing planes, *which are of primary origin,* may be extremely close tôgether (foliation, schistosity) or very far apart (banked condition etc.).

It follows that when in such and similar eruptive massives foliation, divisional planes, fissures, faults, aligned eruption-points etc. are actually established, showing a pronounced and systematic orientation, such occurrence does not *eo ipso* justify the conclusion that these phenomena must have had a secondary origin i.e. were tectonically imposed after (or during) the consolidation of the massive, by the action of tangential or other forces.

As such massives may acquire huge dimensions — even supposing they cannot much surpass those we know already — it follows that our conclusions may fundamentally affect current principles on the origin and nature of the (tectonical) structure of eruptive masses and systems, *(Eruptiv Tektonik ;* (26)) as well as on the deductions based thereon. (Approximate areas of : Kilauea 14 km^2 ; Askja-Knebel 90 km^2 ; Ngorongoro 300 km^2 ; Ringgit 475 km^2 etc. etc.).

We will now put our conclusions to the test of facts which have been well established at Kilauea and in its neighbourhood.

An inter-comparison of several maps and sketches of Kilauea published since 1825 [13] [5] p. 463 ; (24) clearly demonstrates that zonal accretion and corresponding fissuring and faulting of the black ledge actually occurred and proceeded in a direction, *grosso modo,* parallel to the old Kilauea caldera-wall all round the still active remnant of its eruptive channel, Halemaumau.

Such orientation is proved by the trend of Lyman's ridge (e.f-g.h.), which indicates the inner border of DANA's black ledge of 1830 [13] (p. 85) ; by the system of contraction-planes with slight vertical displacements, which trend through the accreted black ledge of Kilauea, concentrical to the crater-wall of Halemaumau. We find our conclusions confirmed, not only by the mode of arrangement of outer-peripherically situated eruption channels round Kilauea as well as round Halemaumau (and also round Kilauea Iki, it would seem), but also by the arrangement of a series of smaller eruption points at or near the border of the black ledge of Kilauea (of 1840) (Fig. 1, *i, k, l, m*), and those within the outer wall of Halemaumau (*p, q, r, s.*). Last but not least, our conclusions are again supported by the directions of trend of the fault-planes going from W. by N. to E. in a wide semi-encompassing curve round the Kilauea-caldera, and comprising Kilauea-Iki and Keanakakoi.

By analogy with occurrences established in old Kilauea and round Halemaumau, it would seem justifiable to conclude that these systems of faults and fissures *round* Kilauea are either remnants of an older caldera-wall or else that they were originated in a black ledge of much larger dimensions, within which Kilauea and its smaller companions may have been the reduced eruption-channels of a larger volcano ; just as Halemaumau is the reduced remnant of old Kilauea.

We should therefore not be surprised to discover that, in and round caldera-areas such as Dygnjufjöll, Santorin and others, tectonic and eruptive phenomena happen to be arranged in perfect harmony of orientation with the directory lines of such areas ; *on the contrary we* *should expect such arrangement.* We therefore emphasize that the establishment of their existence in such areas does not justify to invoke the fact of their occurrence as an irrefutable proof of the contention that such and similar calderas were *generated*, directly or indirectly, by these tectonical or eruptive phenomena (subsidence or explosion).

Such phenomena were *generated*, and they subsequently matured, at least to a large degree, in the body of the pre-existing caldera, as a *causal result* of the way in which it was filled up.

Finally we wish to add a few words to our previous argument. Firstly, it may be mentioned that Kilauea, like Vesuvius, furnished a striking example of the effects of re-fusion of part of its cone and a subsequent flow-back of the re-fused material (Fusion theory of HOCHSTETTER and others). Halemaumau went through such a process when, subsequent to its eruption of 1868, part of the cone all round its eruptive channel, having been re-fused, was capped over completely by a relatively very thin, semi-solid crust. Now, after the subsidence (back flow) of the liquid lava, its thin roofing collapsed; yet the caldera thus formed was, again, not bordered by vertical walls (compare (17) p. 1166).

As instances of blasting-out phenomena, with subsequent cone-pipe enlargement of minor importance (explosion theory (17) (p. 1166) we would mention those which occurred in Vesuvius in 1913 and in Krakatau in 1883.

It would not be difficult to furnish further evidence in support of our contentions, from the eruptive histories of other volcanoes, such as Santorin, Pelée and others. We preferred, however, to restrict our tests principally to well established facts in the history of Vesuvius and Kilauea because they represent two classical and beautiful types of their kind. Moreover, we know no other volcanoes which have been the object of such continuous, detailed, and scientific studies as have these two.

The chosen testing material was therefore of the first order and corresponding demands were therefore made on the arguments by which we had to vindicate our contentions.

The Hague, December 1927.

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Figures placed between ( ) refer to the list below and those placed between [ ] to that at the end of (17).

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